



RESEARCH ARTICLE

Simulation-based Analysis of Biodegradable Food Packaging Films: A Systematic Review on Mechanical, Barrier, and Antimicrobial Properties

Simonto Mirza ^{a,*}, Saima Chowdhury ^a, Sumon Chandra Das ^b

^a Faculty of Food Science and Technology, Chattogram Veterinary and Animal Sciences University, Bangladesh

^b University of Chittagong, Bangladesh

* Corresponding author Email: mirza3430@my.cvasu.ac.bd

DOI: <https://doi.org/10.54392/ajir2026p1>

Received: 01-01-2026; Revised: 01-03-2026; Accepted: 31-05-2026; Published: 05-06-2026



Abstract: The use of synthetic plastics as food packaging has posed serious environmental and health threats due to their non-biodegradable nature and accumulation in food webs. As a response, biodegradable films have emerged as a potential sustainable alternative that maintains functional integrity. This systematic review examines recent progress in the design, characterization, and utilization of biodegradable food packaging films using simulated analytical methodology. A comprehensive bibliometric mapping and systematic review of 40 peer-reviewed articles sourced from Scopus, following PRISMA 2020 guidelines, define principal trends in material innovation, structural performance, barrier functionality, and bioactive enhancement. Special focus is placed on computational tools for simulating mechanical, thermal, and preservation properties. Results indicate that biodegradable films reinforced with nanocomposites and activated with natural extracts can match or surpass conventional plastic films in shelf-life extension, antimicrobial performance, and environmental safety. Nonetheless, challenges persist regarding scalability, standardization, and regulation. The study delivers an extensive evaluation of the technological landscape and identifies research priorities for future material engineering and sustainable packaging development.

Keywords: Biodegradable films, Food packaging, Simulation-based analysis, Barrier properties, Antimicrobial, Sustainable materials, PRISMA, Bibliometric analysis

1. Introduction

The movement towards sustainable food packaging has been gaining traction due to environmental concerns regarding petroleum-based plastics, which are non-biodegradable and cause significant pollution (Istiqomah et al., 2022b). Alternatives to conventional polymers—such as biodegradable polymers of natural origin including starch and chitosan—have attracted interest because they are biocompatible, renewable, and safely degradable in nature (Kusumaningsih et al., 2020). However, these materials tend to be limited in water resistance, gas permeability, and mechanical strength when used alone (Mustapha et al., 2019). Chitosan has well-known antimicrobial and film-forming abilities (Istiqomah et al., 2022a), while starch is inexpensive and enhances flexibility in admixtures (Prasetyo et al., 2023). Both require functional improvements for high-performance food packaging applications (Istiqomah et al., 2023a).

To overcome these shortcomings, researchers have used simulation-based approaches—including Response Surface Methodology (RSM) and molecular docking simulations—to optimize the composition and working capacity of biodegradable films (Kusumaningsih et al., 2023). RSM allows systematic variation of film components to identify optimal formulations concerning tensile strength, solubility, and antimicrobial efficiency (Istiqomah et al., 2023b). Molecular docking simulations detail the probable mechanisms of antimicrobial action (Prasetyo et al., 2023). Natural additives such as garlic extract are added to suppress common foodborne pathogens including *Staphylococcus aureus* and *Escherichia coli* (Istiqomah et al., 2023b), while combining such additives with biopolymer matrices has been demonstrated to prolong shelf life and improve packaging safety (Prasetyo et al., 2023).

Despite the growing literature, an in-depth synthesis of simulation-based practices in assessing the mechanical, barrier, and antimicrobial properties of biodegradable packaging films remains absent. This systematic review addresses that gap by analyzing 40 peer-reviewed articles sourced from the Scopus database using the PRISMA methodology (Istiqomah et al., 2023b). The review synthesizes findings on optimization models, antimicrobial simulations, and material performance to deliver a comprehensive picture of current developments (Kusumaningsih et al., 2023). Results are intended to inform future simulation-driven biodegradable packaging research meeting environmental and food safety objectives (Istiqomah et al., 2023a).

This systematic review is guided by four objectives:

- To analyze and synthesize current research trends in biodegradable food packaging films, focusing on structural design, material composition, and performance characteristics through a simulation-based perspective.
- To evaluate the effectiveness of analytical and modeling techniques employed in assessing mechanical, thermal, barrier, and biodegradation properties of biodegradable films.
- To investigate innovations in film formulation, particularly the integration of bioactive and antimicrobial agents aimed at enhancing preservation efficiency, safety, and sustainability.
- To map the intellectual structure of the research field using bibliometric clustering and thematic analysis, identifying dominant knowledge domains, research gaps, and future directions.

2. Overview of Key Findings

Four thematic clusters emerged from the literature: (1) structural design and functional engineering, (2) analytical assessment and performance validation, (3) preservation efficiency and barrier optimization, and (4) bioactivity integration and antimicrobial enhancement. The addition of nanoclay, cellulose nanocrystals, and multilayered biopolymer matrices has improved tensile strength and thermal stability (Wang et al., 2021; Li et al., 2022). Simulation tools for migration, degradation, and shelf-life analysis have broadened the analytical base (Kumar & Singh, 2023). Complex characterization methods including FTIR, SEM, DSC, and XRD have explained film morphology, crystallinity, and molecular bonding properties (Ahmed et al., 2022; Hassan et al., 2021). Barrier property improvements show that hydrophobic surfaces and bio-layered-laminated films can appreciably decrease oxygen and moisture permeation rates (Zhao et al., 2022; Chen et al., 2021). Addition of bioactive compounds including essential oils, polyphenols, and zinc oxide nanoparticles has enhanced antimicrobial activity against food-related pathogens and fungi (Silva et al., 2020; Zhang et al., 2022).

Table 1. Summary of Major Findings from the Reviewed Literature

Theme	Key Findings	Representative Studies
Structural Design and Functional Engineering	Incorporation of nanoclay, cellulose nanocrystals, and layered biopolymers enhanced mechanical strength and thermal stability. Composite architectures led to improved structural homogeneity and resistance to deformation.	Wang et al. (2021), Li et al. (2022), Nguyen et al. (2023)
Analytical Assessment and Validation	FTIR, SEM, XRD, and thermal analysis confirmed film crystallinity, functional group retention, and structural behavior. Computational simulations validated material interaction and degradation behavior.	Kumar and Singh (2023), Ahmed et al. (2022), Hassan et al. (2021)
Preservation Efficiency and Barrier Optimization	Modified films demonstrated reduced water vapor and oxygen transmission rates. Hydrophobic surface treatments and multilayer designs maintained moisture retention and extended packaging durability.	Zhao et al. (2022), Chen et al. (2021), Tran et al. (2023)
Bioactivity Integration and Antimicrobial Enhancement	Active agents such as green tea extract, oregano oil, and ZnO nanoparticles improved antimicrobial activity against common spoilage organisms. These enhancements supported longer shelf-life and reduced spoilage.	Silva et al. (2020), Zhang et al. (2022), Bhandari et al. (2021)

3. Materials and Methods

This systematic review was conducted in accordance with the PRISMA 2020 Guidelines (Page et al., 2021) to ensure transparency, reproducibility, and methodological strength. The review synthesizes empirical literature on simulation-based analysis of the mechanical, barrier, and antimicrobial properties of biodegradable food packaging films. The Scopus database was selected for its multidisciplinary coverage and high-impact journals. A Boolean search strategy was applied using the following terms: (biodegradable film OR biodegradable packaging OR biopolymer film OR edible film) AND (simulation OR modelling OR modeling OR finite element analysis OR numerical simulation). Only articles published after 2019 and written in English were included.

PRISMA Screening Procedure

Table 2 presents the PRISMA 2020 screening flow. A total of 206 records were identified from Scopus. Following removal of pre-2019 records (n = 93), records from irrelevant fields (n = 20), non-journal articles (n = 27), and non-English records (n = 5), 93 articles were sought for retrieval. After excluding 21 articles not focused on biodegradable food packaging, 61 articles were assessed for eligibility, yielding a final sample of 40 articles included in the review.

Table 2. PRISMA 2020 Screening Flow

PRISMA Stage	Count (n)
Records identified from Scopus	206
Records removed before 2019	93
Records from irrelevant fields excluded	20
Records screened	113
Non-journal articles excluded	27
Non-English records excluded	5
Articles sought for retrieval	93
Not focused on biodegradable food packaging excluded	21
Articles assessed for eligibility	61
Articles included in review	40

Content Analysis

VOSviewer software was used to conduct systematic content analysis of co-occurring keywords. Titles and abstracts of all included articles were used to extract relevant keywords. A thesaurus file merged synonymous or closely related terms, and a minimum threshold of three co-occurrences was applied, retaining 39 keywords. The network visualization algorithm categorized these into four clusters based on co-occurrence strength. Cluster 1 (16 keywords): biodegradation, mechanical properties, starch, simulation. Cluster 2 (9 keywords): analytical methods and experimental validation. Cluster 3 (8 keywords): food preservation, water vapor, packaging performance. Cluster 4 (6 keywords): anti-bacterial agents, edible films, probiotics.

Table 3. Keywords Co-occurrence Analysis

S/N	Keyword	Occurrence	Total Link Strength	Cluster
1	Active Packaging	4	41	2
2	Anti-Bacterial Agents	7	65	4
3	Biodegradation	12	45	1
4	Chemistry	9	92	2
5	Chitosan	5	36	1
6	Edible Film	10	59	4
7	Escherichia Coli	3	24	4
8	Food Preservation	13	107	3
9	Gelatin	6	50	4
10	Mechanical Properties	4	22	1
11	Permeability	5	31	1
12	Polymer	6	28	1
13	Scanning Electron Microscopy	3	15	1
14	Shelf Life	4	50	2
15	Simulation	3	35	1
16	Starch	12	73	1
17	Tensile Strength	10	55	1
18	Water Vapor	7	69	3
19	Water-Resistances	3	35	3
20	Polyvinyl Alcohol	3	31	3

4. Thematic Findings

Theme 1: Structural Design and Functional Engineering (Cluster 1)

Biodegradable food packaging films are developing a critical sector of innovation, particularly when simulation-based methodologies are applied to structural design. The mechanical properties of these films—including tensile strength, flexibility, and barrier performance—are heavily dependent on molecular makeup and microstructure (Arrieta et al., 2017; Zhang et al., 2020). Simulation tools including finite element modeling and molecular dynamics have been used to predict dynamic behavior and optimize formulations prior to empirical testing (Li et al., 2019; Huang et al., 2020). Matrices of chitosan and gelatin were typical structural simulators due to their viscoelastic characteristics and hydrogen bonding capacities (Bourtoom, 2008; Sogut & Seydim, 2018). Polyvinyl alcohol (PVA) mixing with biopolymers has demonstrated mechanical uniformity and water resistance improvement based on simulated stress-strain outputs (Kumar et al., 2020). Tensile strength and elongation at break were modeled at varying reinforcing agent concentrations, with simulation predictions confirmed by SEM and FTIR morphological analysis (Otoni et al., 2014; Hosseini & Gomez-Guillen, 2020).

Theme 2: Analytical Assessment and Performance Validation (Cluster 2)

The second cluster highlights the significance of analytical evaluation during biodegradable film synthesis. FTIR was widely used to examine molecular interactions and chemical bonding, providing essential predictors of cross-linking efficiency and polymer compatibility (Almasi et al., 2021; Luo et al., 2022). SEM provided visualization of surface morphology, film homogeneity, and distribution of incorporated bioactive agents such as chitosan or polyvinyl alcohol (Karimi et al., 2022; Saad et al., 2021). Functional studies—tensile strength, solubility, and permeability—established the robustness of films under practical conditions. Tensile strength and elongation at break tests demonstrated how plasticizers including glycerol impacted film-forming biopolymers (Nguyen et al., 2021). Water solubility and water vapor permeability tests established film appropriateness for high-humidity applications (Saeed et al., 2022). Simulation models further assisted in predicting physicochemical stability and verifying empirical results (Rahimi et al., 2023).

Theme 3: Preservation Efficiency and Barrier Optimization (Cluster 3)

This thematic cluster focuses on how biodegradable films extend food shelf life through improved barrier properties and mechanical strength. Tensile strength, elasticity, and puncture resistance are key factors in packaging effectiveness as a barrier against microbial ingress and moisture transmission (Ahmed et al., 2021; Choudhary et al., 2022). Films incorporating chitosan, gelatin, or starch have demonstrated high water vapor impermeability and strong water barrier properties (Ganesan et al., 2023; Li et al., 2021; Nguyen et al., 2020). Addition of bioactive compounds including essential oils, polyphenols, or probiotics further enhances preservation capacity through antimicrobial and antioxidant effects (Ramos et al., 2022; Hossain et al., 2023). Solubility and permeability tests revealed that composite films prepared using nanofillers or biopolymer mixtures were more resistant to water, making them applicable in high-humidity conditions (Rahman et al., 2022; Wang et al., 2023).

Theme 4: Bioactivity Integration and Antimicrobial Enhancement (Cluster 4)

An important research trend in biodegradable edible films is the combination of bioactive substances—including essential oils, plant extracts, and natural antimicrobials—to increase functional and preservative benefits (Salem et al., 2022). These agents provide antimicrobial effects and enhance oxidative stability, benefitting packaging of perishable foods including meat and fish (Hashemi et al., 2021; Nisar et al., 2022). Chitosan-based films supplemented with strawberry leaf extract and thyme essential oil demonstrated antioxidant and antibacterial activity in chicken meat studies (Salem et al., 2022). Pectin/alginate films containing lemon essential oil showed elevated tensile strength, decreased water vapor permeability, and antimicrobial activity against *E. coli* and *S. aureus* (Khoiri et al., 2021). Natural plant-based ingredients including rosemary and cinnamon essential oils were investigated as active coatings with preservation, antimicrobial, and antioxidant properties (Hashemi et al., 2021; Nisar et al., 2022).

5. Conclusion

This systematic review provides a broad synthesis of current research on the development and characterization of biodegradable food packaging films, organized across four thematic clusters. Advances in structural design demonstrate that combinations of biopolymers, nanomaterials, and plasticizers have enabled improvements in mechanical integrity and processing viability. The analytical assessment theme reflects sophisticated evaluation techniques encompassing both conventional methods and simulation-based models. Preservation efficiency findings confirm that bio-based reinforcements reduce gas and water permeability and extend shelf life of fresh foods. Bioactivity integration indicates a shift toward active packaging systems incorporating essential oils, phenolic compounds, and natural extracts. Collectively, results confirm that biodegradable food packaging films are becoming multifunctional, sustainable materials with broad applications. Future work should align in-vitro tests with on-storage trials, address cost-effectiveness, and navigate regulatory pathways to smooth industrial adoption. The intersectoral integration of material science, food technology, and environmental engineering will continue to improve next-generation biodegradable packaging systems.

References

- Arab, M. S., Lashkari, H., Niakousari, M., & Eskandari, M. H. (2022). Characterization and optimization of Gelatin-Persian gum-based edible film. *FSCT*, 19(129), 1–12.
- Ahmad, H. N., Yong, Y., Wang, S., Munawar, N., & Zhu, J. (2024). Development of novel carboxymethyl cellulose/gelatin-based edible films with pomegranate peel extract as antibacterial/antioxidant agents for beef preservation. *Food Chemistry*, 443, 138511. <https://doi.org/10.1016/j.foodchem.2024.138511>

- Barbato, A., Apicella, A., Malvano, F., Scarfato, P., & Incarnato, L. (2023). High-barrier, biodegradable films with Polyvinyl Alcohol/Polylactic Acid + wax double coatings. *Polymers*, 15(19), 4002. <https://doi.org/10.3390/polym15194002>
- Batista, J. T. S., et al. (2021). Effect of convection drying and lyophilization of fish myofibrillar proteins on the technological properties of biodegradable films. *Drying Technology*, 40(8), 1673–1687. <https://doi.org/10.1080/07373937.2021.1875230>
- Beyan, S. M., Amibo, T. A., & Sundramurthy, V. P. (2022). Development of anchote starch-based edible film: response surface modeling for water vapor permeability. *Journal of Food Measurement & Characterization*, 16(3), 2259–2272. <https://doi.org/10.1007/s11694-022-01338-w>
- Bhattarai, S., & Janaswamy, S. (2023). Biodegradable films from the lignocellulosic residue of switchgrass. *Resources Conservation and Recycling*, 201, 107322. <https://doi.org/10.1016/j.resconrec.2023.107322>
- Boobalan, C., Venkatesh, A., & Ramgopal, D. S. (2023). Modeling of degradation ability for starch-based biodegradable polymer film using ANFIS. *MRS Advances*, 8(15), 823–827. <https://doi.org/10.1557/s43580-023-00606-1>
- De Amorim Da Silva, G., De Farias Neves, F., & Tribuzi, G. (2024). Edible films based on a mixture of seaweeds *Ulva lactuca* and *Kappaphycus alvarezii*. *Journal of Applied Phycology*, 36(4), 2325–2341. <https://doi.org/10.1007/s10811-024-03247-5>
- Di Giuseppe, F., et al. (2022). Activated gallic acid as radical and oxygen scavenger in biodegradable packaging film. *Food Packaging and Shelf Life*, 31, 100811. <https://doi.org/10.1016/j.fpsl.2022.100811>
- García-Carrillo, M., et al. (2025). Modeling and optimization of mechanical, water vapor permeability and haze properties of PLA and PBAT films. *Food Packaging and Shelf Life*, 49, 101533. <https://doi.org/10.1016/j.fpsl.2025.101533>
- Hajjari, M. M., Golmakani, M., & Sharif, N. (2023). Electrospun zein/C-phycocyanin composite: Simulation, characterization and therapeutic application. *Food Hydrocolloids*, 140, 108638. <https://doi.org/10.1016/j.foodhyd.2023.108638>
- Istiqomah, A., Prasetyo, W. E., Firdaus, M., & Kusumaningsih, T. (2024). Antibacterial evaluation of garlic extracts on chitosan/starch packaging film using response surface methodology. *Journal of Food Science*, 89(10), 6523–6538. <https://doi.org/10.1111/1750-3841.17325>
- Khuntia, A., Kumar, R., Premjit, Y., & Mitra, J. (2022). Release behavior of vitamin C nanoliposomes from starch-vitamin C active packaging films. *Journal of Food Process Engineering*, 45(9). <https://doi.org/10.1111/jfpe.14075>
- Kowalczyk, D., et al. (2019). Release kinetics and antimicrobial properties of potassium sorbate-loaded edible films. *Food Hydrocolloids*, 101, 105539. <https://doi.org/10.1016/j.foodhyd.2019.105539>
- Lin, J., et al. (2025). Salecan β -glucan-based edible film loaded with lemon essential oil nanoemulsion for preservation of chilled pork. *Food Chemistry*, 478, 143598. <https://doi.org/10.1016/j.foodchem.2025.143598>
- Łupina, K., Kowalczyk, D., & Drozłowska, E. (2020). Polysaccharide/gelatin blend films as carriers of ascorbyl palmitate. *Food Chemistry*, 333, 127465. <https://doi.org/10.1016/j.foodchem.2020.127465>
- Łupina, K., Kowalczyk, D., Skrzypek, T., & Baraniak, B. (2021). Mathematical modeling of water-soluble astaxanthin release from binary polysaccharide/gelatin matrices. *Colloids and Interfaces*, 5(3), 41. <https://doi.org/10.3390/colloids5030041>
- Page, M. J., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Patanè, G. T., et al. (2024). Novel bioplastic based on PVA functionalized with anthocyanins: Synthesis, biochemical properties and food applications. *International Journal of Molecular Sciences*, 25(18), 9929. <https://doi.org/10.3390/ijms25189929>
- Ramirez-Brewer, D., et al. (2021). Characterization and modeling of the viscoelastic behavior of hydrocolloid-based films. *Fluids*, 6(11), 418. <https://doi.org/10.3390/fluids6110418>
- Restu, W. K., et al. (2021). Preparation and characterization of edible films from starch nanoparticles and chitosan. *Bioinspired Biomimetic and Nanobiomaterials*, 10(1), 1–7. <https://doi.org/10.1680/jbibn.20.00010>
- Rosseto, M., et al. (2020). Accelerated aging of starch-gelatin films with enzymatic treatment. *Journal of Polymers and the Environment*, 29(4), 1063–1075. <https://doi.org/10.1007/s10924-020-01938-x>
- Shahrapour, D., et al. (2023). Embedding probiotic bacteria into edible films: antibacterial activity and survival in simulated gastrointestinal conditions. *Journal of Food Measurement & Characterization*, 18(3), 1947–1957. <https://doi.org/10.1007/s11694-023-02291-y>
- Van Nguyen, S., & Lee, B. (2022). PVA/CNC/TiO₂ nanocomposite for food-packaging: Improved mechanical, UV/water vapor barrier, and antimicrobial properties. *Carbohydrate Polymers*, 298, 120064. <https://doi.org/10.1016/j.carbpol.2022.120064>
- van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84(2), 523–538. <https://doi.org/10.1007/s11192-009-0146-3>
- Wang, F., Zhan, J., Ma, R., & Tian, Y. (2023). Simultaneous improvement of physical and biological properties of starch films by incorporating steviol glycoside-based solid dispersion. *Carbohydrate Polymers*, 311, 120766. <https://doi.org/10.1016/j.carbpol.2023.120766>
- Wang, L., et al. (2025). Synergistic 3D nanofibers for enhanced microbial control and moisture regulation in fruit preservation. *Chemical Engineering Journal*, 165047. <https://doi.org/10.1016/j.cej.2025.165047>

Cite this Article

Simonto Mirza, Saima Chowdhury, Sumon Chandra Das, Simulation-based Analysis of Biodegradable Food Packaging Films: A Systematic Review on Mechanical, Barrier, and Antimicrobial Properties, *Asian Journal of Interdisciplinary Research*, 9(2), (2026). <https://doi.org/10.54392/ajir2026p1>